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Understanding land use change impacts on microclimate using Weather Research and Forecasting (WRF) model

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ABSTRACT

To explore potential climatic consequences of land cover change in the Kolkata Metropolitan Development area, we projected microclimate conditions in this area using the Weather Research and Forecasting (WRF) model driven by future land use scenarios. Specifically, we considered two land conversion scenarios including an urbanization scenario that all the wetlands and croplands would be converted to built-up areas, and an irrigation expansion scenario in which all wetlands and dry croplands would be replaced by irrigated croplands. Results indicated that land use and land cover (LULC) change would dramatically increase regional temperature in this area under the urbanization scenario, but expanded irrigation tended to have a cooling effect. In the urbanization scenario, precipitation center tended to move eastward and lead to increased rainfall in eastern parts of this region. Increased irrigation stimulated rainfall in central and eastern areas but reduced rainfall in southwestern and northwestern parts of the study area. This study also demonstrated that urbanization significantly reduced latent heat fluxes and albedo of land surface; while increased sensible heat flux changes following urbanization suggested that developed land surfaces mainly acted as heat sources. In this study, climate change projection not only predicts future spatiotemporal patterns of multiple climate factors, but also provides valuable insights into policy making related to land use management, water resource management, and agriculture management to adapt and mitigate future climate changes in this populous region.

1. Introduction

Microclimate refers to “the ambient physical conditions due to either atmospheric variables or exchanges with other bodies over a period of time representative of all the conditions determined by the natural and manmade forcing factors” (Camuffo, 1998, p8). Atmospheric variables, such as temperature, precipitation, and sensible and latent heat fluxes are important for human society. Meanwhile, these variables are sensitive to anthropogenic activities that modify land surface properties and land-atmosphere connections (Hartig et al., 1997; McMichael et al., 2006).

Conversions of wetlands to other land use types could alter local hydrological cycling and influence the microclimate of regions (Carrington et al., 2001; Bai et al., 2013b). Since the 20th century, large areas of wetlands have been replaced by agricultural lands for food production to support increasing populations in different countries (Bai et al., 2013a; Li et al., 2013). The conversion rate has been accelerated dramatically in recent decades due to reductions in runoff and increase in evapotranspiration as a result of climate change (Hartig et al., 1997; Rijsberman and De Silva, 2006). Wetland drainage for agriculture has significantly reduced water tables and water-storage capacity of wetlands. Wetland losses could substantially alter evapotranspiration and runoff, and thus influence heat change between land and the atmosphere (Kalnay and Cai, 2003; Bartzen et al., 2010). Shifts of wetlands to croplands also result in changes in structure and function of the vegetation layer, which further influences energy fluxes in the climate system (Kutzbach et al., 1996; Stohlgren et al., 1998; Carrington et al., 2001).

Conversion of wetlands to built-up areas increases impervious surfaces that enhance surface runoff generation, and thus influence regional water cycling. Soil water changes following conversions from wetland vegetation to paved surface could significantly alter sensible and latent heat fluxes (Kueppers et al., 2008). Along with

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expansion of built-up areas, elevated temperature has been reported due to the urban heat island (UHI) effect, which is mainly caused by increased heat emissions from human-related sources (Weng et al., 2004; Lamptey et al., 2005; Chen et al., 2006; Tan et al., 2010). Enhancement of precipitation in the downwind areas of urbanized land has been observed and attributed to urbanization (Shepherd et al., 2002).

Land use and land cover (LULC) change impacts on microclimate can be quantified based on observation (Shepherd et al., 2002; Mote et al., 2007; Mitra et al., 2012) and modeling (Stohlgren et al., 1998; Trusilova et al., 2008; Shepherd et al., 2010; Wang et al., 2015). The Weather Research and Forecasting (WRF) model is a fully compressible, non-hydrostatic numerical weather prediction system used for weather forecasting and atmospheric research (Skamarock et al., 2008; Hong et al., 2009). Various studies have employed the WRF model to assess the impact of LULC dynamics on microclimate (Hong et al., 2009; Mahmood et al., 2011; Wang et al., 2015). Zhang et al. (2010) employed WRF model to investigate the microclimate change in China, and found that conversion of croplands to urban areas increased both temperature and precipitation but decreased surface humidity, with a stronger influence in summer than in winter. Through incorporating Noah Urban Canopy with WRF model, Grossman-Clarke et al. (2010) explored contributions of urban expansion to near-surface air temperature and concluded that the maximum temperature increase occurred when irrigated agricultural lands were replaced by developed areas.

Under the pressure of rapid population growth, it is common that agricultural and built-up areas expand at the expense of wetlands because drained wetlands could be easily converted to cropland or urban areas (Scoones, 1991). There is a pressing need to evaluate to what extent the microclimate can be altered due to wetland shrinkage. Objective of this study is to elucidate influences of LULC change, particular wetland conversion, on temperature, precipitation, latent heat flux, sensible heat flux, and albedo in Kolkata city.

2. Study area

The Kolkata Metropolitan Development Area (KMDA) is an economic and cultural center of north-eastern India. Latitude of this region ranges from 22°19′ N to 23°01′ N and longitude from 88°04′ E to 88°33′ E, with an area of approximate 1851 km^2. It is one of the largest urban centers in Asia, and includes the Kolkata Municipal Corporation (KMC), 38 other municipalities, 77 non-municipal urban towns, 16 suburban districts, and 445 rural districts (Dasgupta and De, 2007). The KMDA has a tropical climate with hot and humid summers and dry and cool winters. Annual mean temperature of this region is 24.8 °C and average precipitation is 1600 mm yr^{-1} with a short and intense rainfall period during the monsoon season from June to September (Dasgupta and De, 2007; Mitra et al., 2012).

KMDA experiences a rapid urban population growth in recent decades. As reported by UN Habitat (2013), total population of this region was 15.55 million in 2010 and increased by about 97.08% from 1975 (Taubenböck et al., 2009). The continuous population growth has stimulated rapid urban expansion, and converted large areas of natural ecosystems, such as the East Kolkata Wetlands (EKWs) located in the eastern part of KMDA, to developed lands (Bhatta, 2009; Parihar et al., 2013; Sharma et al., 2015). EKWs are important land covers in India and were designated as the "Wetland of International Importance" under the Ramsar Convention in 2002 (Parihar et al., 2013). However, total wetland areas decreased substantially in recent decades due to population increase and intensifying anthropogenic disturbances. Conversion of wetlands to other land covers in and around Kolkata city not only affects ecological integrity of this region, but also alters microclimate and changes in rainfall patterns (Mitra et al., 2012).

3. Material and methodology

3.1. Methods

Effects of wetland shrinkage on the microclimate of Kolkata city were explored with the WRF model driven by two land use scenarios. This model allows for idealized simulation based on existing data and simplified analytic orography as well as real weather simulation using observational data. WRF 3.5.1 in a one-way nesting technique was applied and considered four domains (domain 1 to domain 4) with spatial resolutions ranging from 27 km (domain 1) to 1 km (domain 4, Fig. 1A) in this study. KMDA is located in the center of domain 4 (Fig. 1B).

A series of physics components were developed for the model simulation, including microphysics, radiation, surface layer and boundary layer parameterization, as well as cumulus parameterization. Both sophisticated physics and simple physics schemes are included in the modeling framework (Skamarock et al., 2008). Selections of schemes are important for ensuring model performances across diverse scales and in different regions (Chen and Dudhia, 2000). For example, Kumar et al. (2010) compared performances of three cumulus convection schemes in Indian rainfall forecast and found that the Betts-Miller-Janjic scheme had the best performance compared to Kain-Fritsch and Grell-Devenyi schemes in the monsoon region and reconstructed monsoon precipitation well at multi-scales (Kumar et al., 2010). Noah Land Surface Model (Noah LSM) is a widely used land-surface layer scheme, which links atmospheric characteristics with land-surface properties (i.e., land covers) to evaluate heat transport and moisture dynamics (Hong et al., 2009). This scheme has been successfully applied for predicting temperature and precipitation changes in response to LULC change (Borge et al., 2008; Jiang et al., 2008; Hong et al., 2009; Grossman-Clarke et al., 2010). Based on previous investigations, we selected schemes for this study as listed in Table 1.

3.1.1. Scenario analyses

Scenario analyses were employed to quantify impacts of wetland conversions on microclimate changes. Model simulation was conducted during November 2011 to January 2012, which is the dry season in the study area. Simulation of this period would minimize precipitation anomaly caused by monsoon rainfalls. The meteorological input data (Global Forecast System) for WRF model simulation were provided by the National Centers for Environmental Prediction (NCEP) (http://rda.ucar.edu/datasets/ds083.2/). This dataset has a spatial resolution of a 1-degree by 1-degree, and a temporal resolution of 6 h. For LULC inputs, the default 33-category U.S. Geological Survey (USGS) Land Use/Land Cover system in WRF was used for our model simulation.

A real weather simulation was first conducted to simulate microclimate in KMDA during the chosen period. Physical parameters that were used to characterize land surface properties, including albedo, soil moisture, surface emissivity, surface roughness, thermal inertia, and surface heat capacity were included in the LANDUSE.TBL file; and vegetation parameters for each land covers, including green vegetation fraction, rooting depth, minimum and maximum leaf area index through the year, and minimum and maximum background albedo through the year, were included in the VEGPARM.TBL file. Default parameter values were used in the real weather simulation. In addition to this simulation, we had two addition scenario analyses to evaluate land use change impacts on the climate system.

Land use scenario 1 assumes that all wetlands and croplands

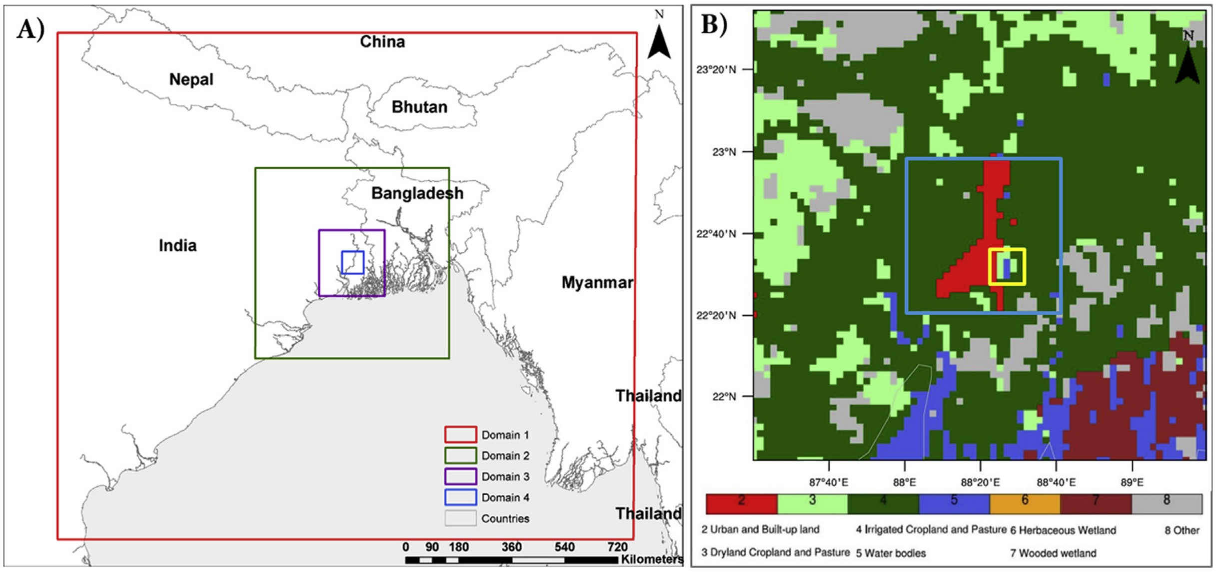

Fig. 1. A) Four nested domains selected for model simulation and B) land cover types in domain 3 and domain 4. Urban and built-up land in domain 4 (blue frame in B) is Kolkata Metropolitan Development area and the yellow frame shows the location of East Kolkata wetlands. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Model configuration and physics schemes.

Number of domains	4
Resolution	27 km (domain d01), 9 km (domain d02), 3 km (domain d03), 1 km (domain d04)
Number of grid points	70 × 70 (all domains)
Map projection	Mercator
Central point of the domain	Central latitude: 22.66° N Central longitude: 88.33° E
Microphysics scheme	Single-Moment 5-class microphysical scheme
Land-surface layer scheme	Noah land surface model
Radiation scheme (long wave)	Rapid radiative transfer model for GCM (RRTMG)
Radiation scheme (short wave)	Dudhia scheme
Boundary layer physics	Yonsei University scheme
Cumulus convection scheme	Betts-Miller-Janjic scheme

were converted to built-up lands. Other LULCs were kept unchanged as that of in 2011. To do so, physical and vegetation parameters of “dryland cropland and pasture”, “irrigated cropland and pasture”, “herbaceous wetland”, and “wooded wetland” were changed into parameters of “urban and build-up land” in the LANDUSE.TBL and the VEGPARM.TBL files. One thing that should be noted here is the failure of distinguishing EKWs from water bodies in the default LULC system. Although the system successfully classified most wetlands around KMDA, the misclassification of EKWs (Fig. 1B) may lead to uncertainties in investigating micro-climate change responses to wetland conversions.

Land use scenario 2 assumes that wetlands and dryland cropland were converted to irrigated cropland. Other LULCs were kept unchanged as that of 2011. For this scenario, physical and vegetation parameters of “dryland cropland and pasture”, “herbaceous wetland”, and “wooded wetland” were replaced with parameters of “irrigated cropland and pasture” in the LANDUSE.TBL and VEGPARM.TBL tables.

Daily temperature, precipitation, latent heat flux, sensible heat flux, and albedo in the land use scenario 1 and 2 were compared with the variables in the real weather simulation to explore contributions of land conversions to micro-climate change.

3.1.2. Model performance evaluation

Model performance evaluation is an important step for model application and development. In this study, we evaluated WRF performances by comparing model simulations against observational data. Three criteria were applied to evaluate temperature simulation. The first one is the coefficient of determination (r^2) that obtained from linear regressions between simulation and observation. The second criterion used in the evaluation is the Theil's inequality coefficient (U, Theil, 1966):

$$U = \sqrt{\frac{\sum_{i=1}^{n} \Delta_i^2}{\sum_{i=1}^{n} Observed_i^2}} \quad (1)$$

where Δ is the difference between the observed and simulated data and n is the total number of the compared data. U values close to 0 suggest perfect model performances.

Model efficiency (ME) was used as the third criterion:

$$ME = 1 - \frac{\sum_{i=1}^{n} \Delta_i^2}{\sum_{i=1}^{n} \left(Observed_i - \overline{Predicted}\right)^2} \quad (2)$$

where a perfect fit between the observed and predicted data is suggested by ME when this value is equal to 1. The model

performance is not better than an average value if *ME* is 0 and is poor if *ME* is negative.

The coefficient of determination was also used for evaluating precipitation simulation. Unlike temperature evaluation that used all simulated data, the determinate of r^2 only included days with measurable precipitation data. Besides r^2, bias precipitation factor was applied because the dataset did not follow a normal distribution. The bias factor is the ratio of total number of correctly forecasted precipitation occurrence to the total number of observed precipitation occurrence (Duethmann et al., 2013).

3.2. Data

Climate variables, such as daily precipitation and daily temperature from November 2011 to January 2012 were collected from the Dumdum station (2239′ N, 8826′W) for model performance evaluation. The station is located at the central parts of the Kolkata city. In addition, NCEP/NCAR reanalysis data with a 2.5° × 2.5° resolution were used as references for the comparison between observed and simulated data.

4. Results and discussion

4.1. Model performance evaluation

The simulated temperature data in domain 1 was compared to reanalysis data at the 2.5° × 2.5° resolution (Fig. 2). The general spatial variations were consistent between the two datasets. During the study period the highest temperature was found in the ocean areas with a mean daily temperature above 25 °C; while the lowest temperature was observed in the Tibet area with a mean daily temperature below −15 °C. The temperature of inland India was in a range between 15 °C and 25 °C. However, our modeled temperature showed a higher variation than the reanalysis data in Myanmar.

Simulated heat fluxes were also evaluated against the reanalysis data (Fig. 3). In this study, latent heat flux refers to energy exchanges between land surface and the atmosphere, which is used for water phase changes through evapotranspiration and subsequent condensation. Sensible heat flux refers to energy fluxes during temperature changes of the land surface. Both simulated data and reanalysis data showed high heat fluxes in oceans while relatively low fluxes in inland regions (Fig. 3A and B). Similar to temperature, model estimates showed a higher variation in Myanmar than the reanalysis data. For sensible heat flux, the ocean had relatively low values compared with inland areas (Fig. 3C and D). Simulated heat fluxes varied from 40 W m^{-2} to 60 W m^{-2}, which were comparable with reanalysis data. However, model simulations had higher values in the northern areas (Himalaya Mountain) than the reanalysis data. The discrepancies suggested that a further selection on schemes related to sensible heat flux may be needed for improving model simulation in high altitude areas.

Model performances in simulating temperature and precipitation were also evaluated against field data at the Dumdum station. In general, the model provided decent representations of the two climate factors. Determination of coefficient for temperature was 0.79 and the correlation was statistically significant. The Theil's inequality coefficient for temperature was 0.067, which suggested that temperature was well simulated by the model. In addition, ME value (0.708) was close to 1, further demonstrating that the real-simulation reasonably reproduced observed data. Determination of coefficient for precipitation simulation was 0.659 and also suggested that the simulated precipitation events matched with the observation well. Bias between model simulation and field data (31%) indicated that there were discrepancies between simulated and observed precipitation.

The WRF model has been widely used in investigating regional meteorological conditions (Evans et al., 2012; Shrivastava et al., 2015; Yang et al., 2015). A variety of methodologies have been developed to evaluate the performance of the model (Jankov et al., 2005). Results of the evaluation in this study is consistent with previous studies that showed less bias in temperature simulation than that in precipitation (Evans et al., 2012). In addition to uncertainties in input land cover data and temporal/spatial resolutions of these data, physical options in model parameterization could be an important reason for the discrepancies between model simulation and observations (Shrivastava et al., 2015). In the future,

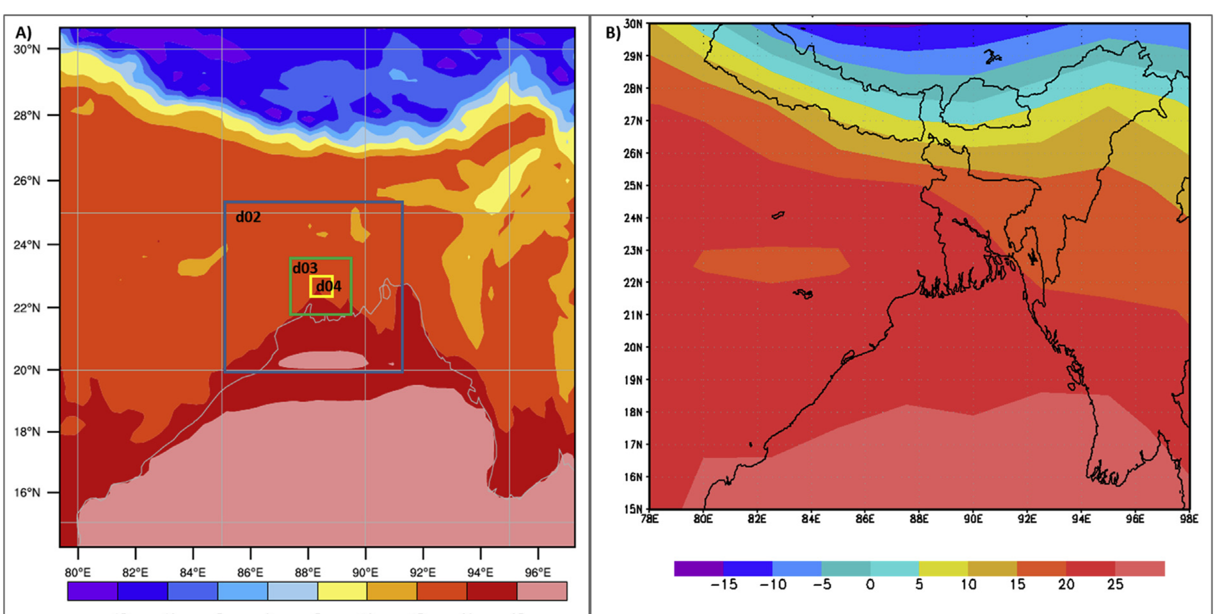

Fig. 2. Comparison of mean daily temperature in domain 1 between A) simulated data and B) NCEP/NCAR reanalysis, from November 2011 to January 2012.

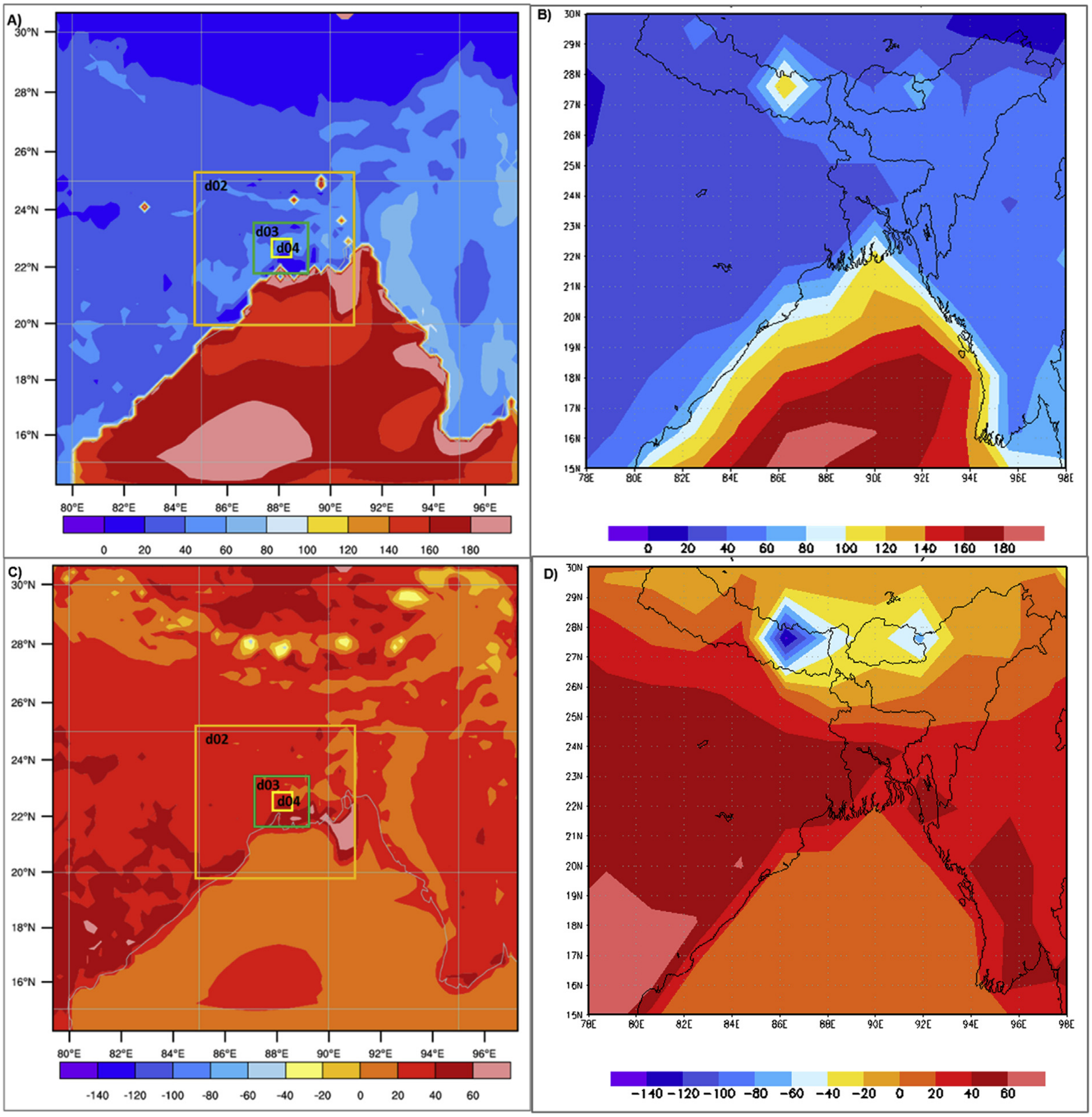

Fig. 3. Comparison of mean daily latent heat flux in domain 1 between A) simulated data and B) NCEP/NCAR reanalysis and mean daily sensible heat flux in domain 1 between C) simulated data and D) NCEP/NCAR reanalysis, from November 2011 to January 2012.

model performance could be potentially improved by optimizing multiple parameterization schemes (Lee et al., 2011).

4.2. Real weather simulation

Fig. 4 presents the spatial distributions of simulated meteorological variables from the real weather simulation. Due to the UHI effect, the KMDA area had a much higher average temperature than the remaining parts of domain 4 (Yap and Oke, 1974; Stewart and Oke, 2009). Temperature in southern coastal regions was also higher than that in the land parts. Lowest temperature during the study period occurred in eastern areas of this region. Results indicated that the UHI effect and the different specific heats between land and oceans may be two factors determining the thermal environment in this region (Lo et al., 2007). Precipitation in the southern parts of this region (domain 4) was higher than the northern areas, while urban precipitation was not different from that in rural areas. One possible explanation is that regional circulation plays a more important role in determining spatial patterns of precipitation than land cover (Zhang et al., 2010).

Patterns of the latent heat fluxes were contrasting with that of temperature. In the KMDA and the southern parts of domain 4 where heat fluxes from land to the atmosphere were low, average temperatures were mainly over 19 °C. Conversely, in cropland regions which showed much higher latent heat fluxes (generally over 40 W m^{-2}), temperatures were generally below 19 °C. Low water contents and vegetation transpiration in built-up regions were mainly responsible for the low latent heat fluxes in urban areas. Contrasting patterns between latent heat flux and temperature was in line with the previous investigations that reported the cooling effects of plantation (Lo et al., 2007; Ng et al., 2012). In spite of the high latent fluxes at the EKWs, temperature in this region was

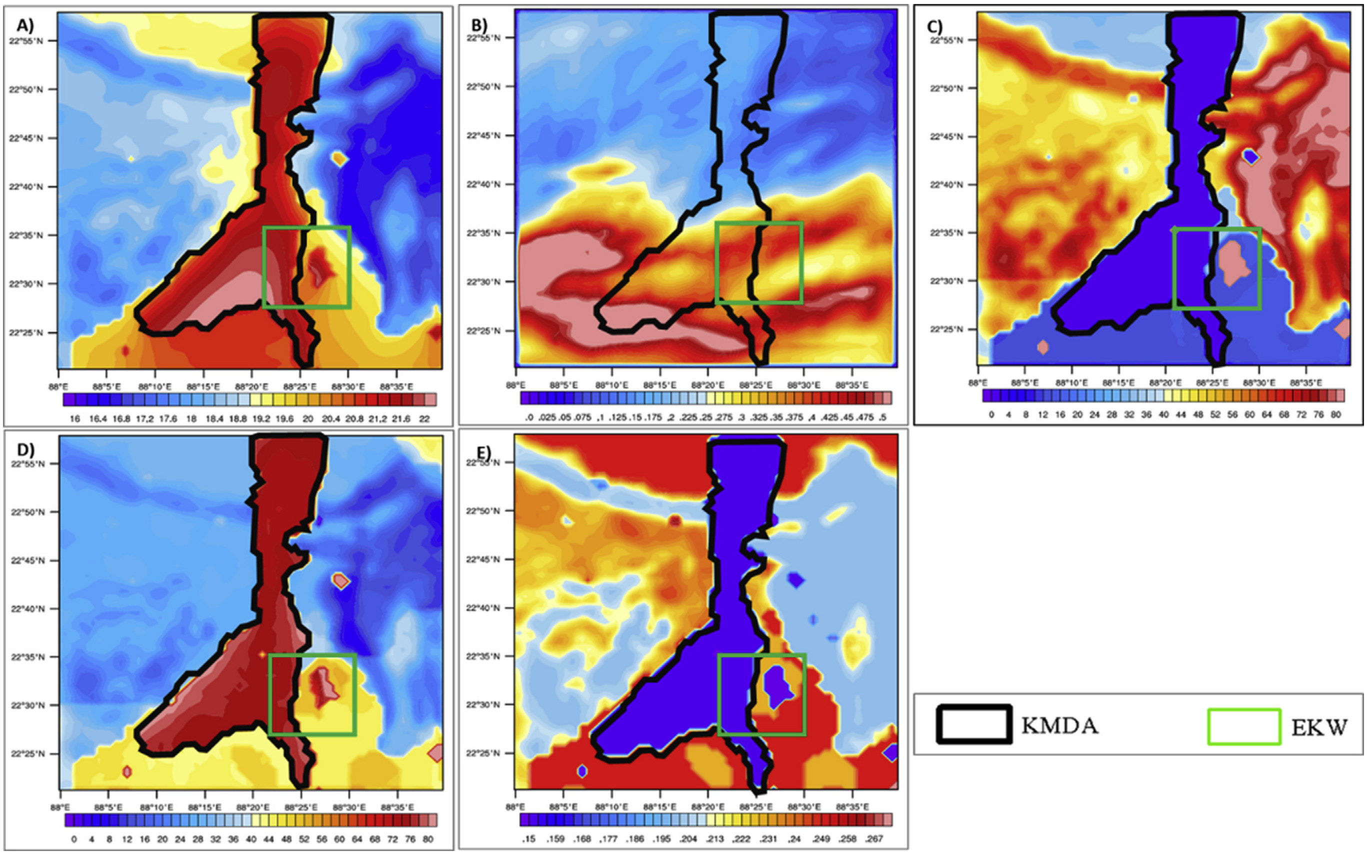

Fig. 4. Spatial variation in climate variables in the real simulation in domain 4. A) temperature (°C), B) precipitation (mm), C) latent heat flux (W m^{-2}), D) sensible heat flux (W m^{-2}), and E) albedo, from November 2011 to January 2012.

comparable with that in urban areas. Possible explanation could be derived from sensible heat flux patterns. As depicted in Fig. 4D, water body of EKWs had high sensible heat fluxes in winter, and thus resulted in the relatively higher temperature (Sánchez-Carrillo et al., 2004). Due to the low specific heat in urban area, urban areas tended to be net sources of sensible heat, whereas the remaining parts of domain 4 tended to obtain energy from the atmosphere to support evapotranspiration.

4.3. Spatial variability of selected variables in response to LULC change

Model simulation indicated that changing land covers would substantially altered multiple meteorological factors and associated water and energy fluxes. Fig. 5 demonstrated differences in temperature of the two LULC change scenarios relative to the real weather simulation. Land conversion from wetlands and croplands to urban areas resulted in over 3.0 °C increases of temperature in most parts of domain 4. Land conversion has been considered as one of the most significant and far-reaching modifications to natural ecosystems (Van Asselen and Verburg, 2013). Built-up areas dramatically alter surface areas, thermal characteristics, and moisture pathways and tend to add extra energy supply to ecosystems (Grimmond, 2007). Our simulation showed that if the study area was totally urbanized, average temperature would increase by 1.2–4 °C (Fig. 5A). This result is consistent with the previous investigations for major Asian cities (Taniguchi et al., 2007).

Comparison between scenario 2 and real weather simulation indicated that expanding irrigated croplands mainly resulted in reductions in temperature (Fig. 5B). In most parts of domain 4, decreased temperature was less than 0.3 °C. Reduction in temperature in scenario 2 could partly be attributed to the enhanced evapotranspiration and heat capacity in irrigated croplands when compared with wetlands (Kalnay and Cai, 2003).

Note that the UHI and cooling effects not only affected areas with changing land covers, but also happened in the KMDA region. High temperature in urban areas was further enhanced by urban sprawls in the adjacent rural regions (Fig. 5A). Expansion of irrigated area would contribute to reducing urban temperature. This study further confirms the far-reaching impacts of land conversion on regional climate systems and suggests that a systematic analysis considering both direct and indirect impacts from land conversions would be necessary for assessing potential consequences of LULC change in the future (Feddema et al., 2005).

Impacts of LULC changes on precipitation are complex (Mahmood et al., 2010). Land conversions induced both increased and decreased precipitation (Fig. 6). For the urbanization scenario, maximum rainfall rates tended to move toward northeastern areas and lead to increased rainfall in the northeastern parts of domain 4. This phenomenon may be caused by the downwind effect. In the real weather simulation, precipitation was much higher on Jan. 7th and Jan 8th with southwest winds than in other days. The low-level prevailing wind tended to advect the moisture and low level convergence downstream urbanized areas and thus enhance precipitation in the downwind areas of urban lands (Shepherd et al., 2002). Therefore, rainfall generally increased in the southern parts, but reduced in the central-northern areas of KMDA. Northern regions of the KMDA also received higher rainfall relative to the real weather simulation. For the EKWs, precipitation was mainly

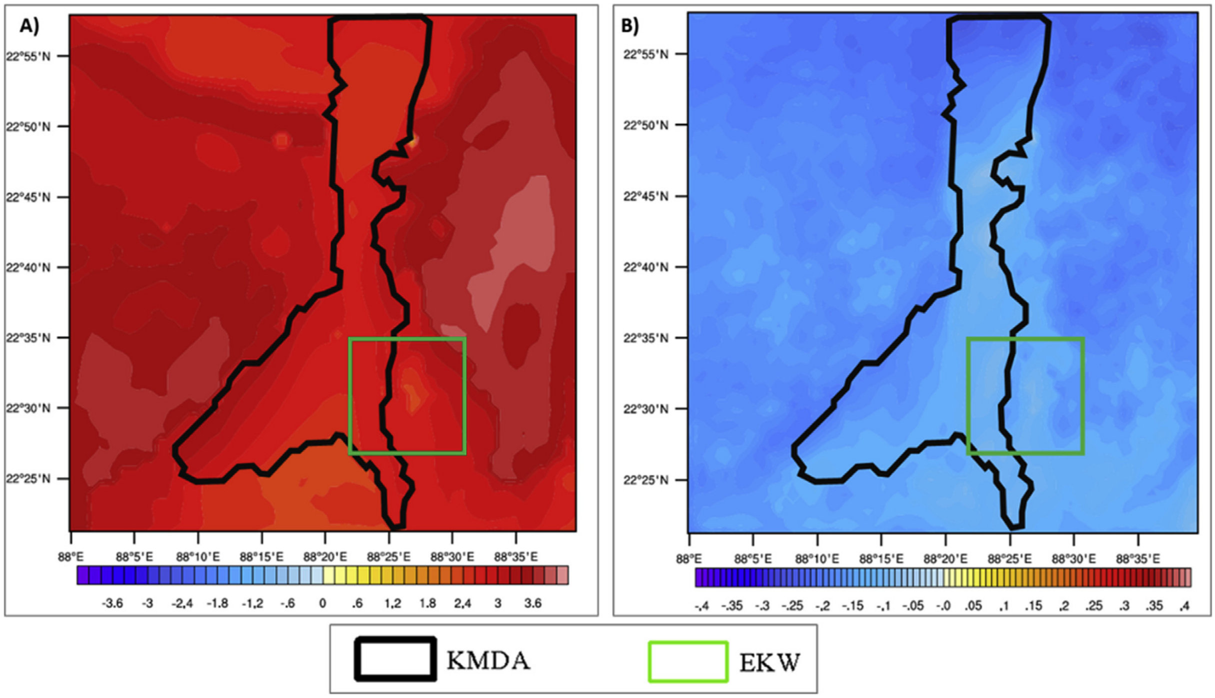

Fig. 5. Mean daily temperature (°C) changes following LULC change in domain 4 from November 2011 to January 2012. A) Scenario 1 minus real weather simulation, B) Scenario 2 minus real weather simulation.

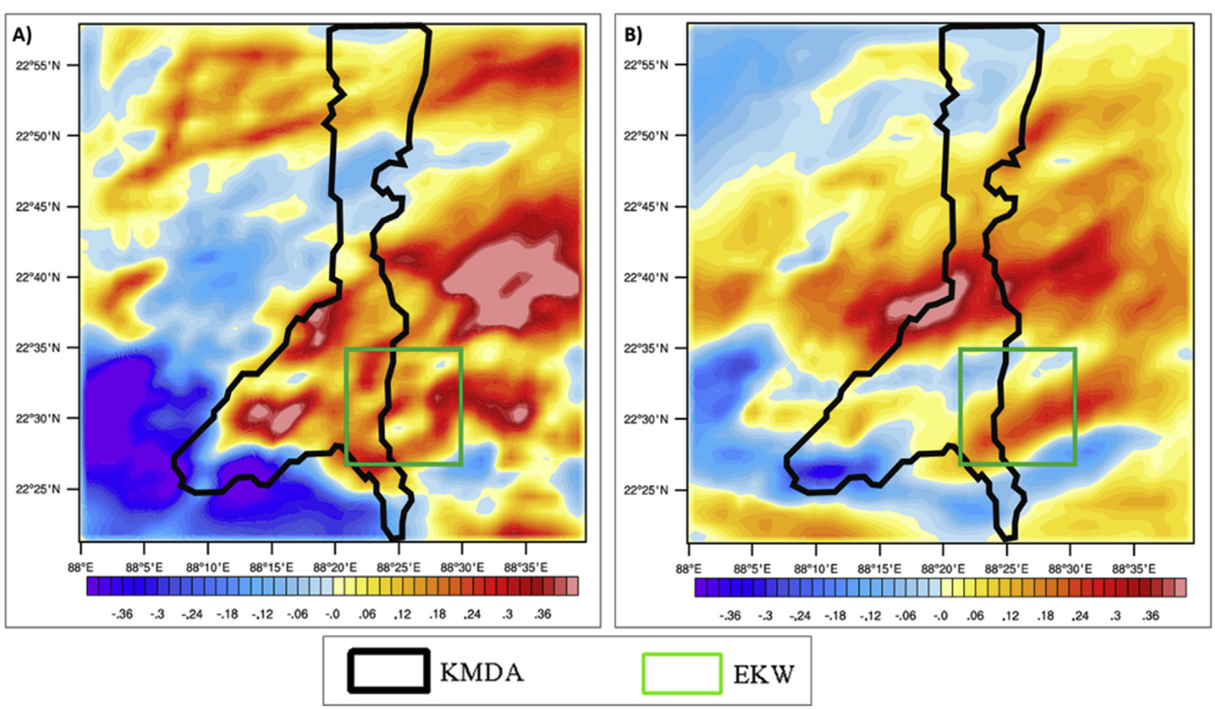

Fig. 6. Mean daily precipitation changes (mm) following LULC change in domain 4 from November 2011 to January 2012. A) Scenario 1 minus real weather simulation, B) Scenario 2 minus real weather simulation.

enhanced, except for the central areas of this region.

Impacts of urbanization on rainfall patterns have been widely documented, especially for major metropolitan areas. In line with previous investigations, this study also revealed that responses of precipitation to urbanization were not as evident as that of temperature (Tayanc and Toros, 1997). Underlying mechanisms regulating rainfall responses to urbanization have not been adequately explored. Urbanization induces a series of complex changes in land surface roughness, soil moisture, and exchange of water and energy between land and the atmosphere (Lamptey et al., 2005). These changes can either offset or enhance each other and thus further complicate the spatial patterns of

precipitation (Trusilova et al., 2008).

Precipitation increased by approximately 35% in domain 4 due to the expansion of croplands. This change is in line with previous studies which reported that irrigation could potentially increase precipitation (Deangelis et al., 2010). Maximum rainfall rates tended to move to the central parts of domain 4. Most parts of the central and eastern areas experienced enhanced rainfall, while the southwestern and northwestern parts of domain 4 had decreased precipitation (Fig. 6B). In the KMDA, precipitation showed significant increases in the center of the city but decreases in the northern and southern areas. In the southeast corner of the city, precipitation was significantly reduced. For the EKWs, increases in irrigated cropland enhanced precipitation in most parts of this area.

Previous studies reported that expansion of irrigation had positive impacts on precipitation (Wei et al., 2012). Increases in precipitation are possibly caused by enhanced evapotranspiration following expanded irrigated lands (Deangelis et al., 2010). Similar to the impacts of urbanization, complexity of precipitation changes in cropland expansion may also due to differences in land surface for different areas (Wei et al., 2012), or complex changes in atmospheric circulations (Kueppers and Snyder, 2012).

The majority of domain 4 received reductions in latent heat fluxes under the urbanization scenario (Fig. 7A). For the KMDA and the southern parts of domain 4 where built-up land cover was the primary land cover, latent heat flux did not show much difference. In the eastern and western parts of domain 4 where cropland was the major land cover before urbanization, latent heat flux was generally reduced. Changes in latent heat fluxes may be caused by the changes in soil water content (Zhang et al., 2010). Conversions from natural ecosystems, especially wetlands, to paved surfaces alter the natural water cycling processes such as water infiltration and associate soil moisture dynamics. High percentage of impervious surface area favors surface runoff generation but reduces evapotranspiration (Trusilova et al., 2008).

Response of latent heat fluxes to land conversions from wetlands and dry croplands to irrigated croplands showed significant heterogeneity in domain 4 (Fig. 7B). Eastern parts of this area experienced increased heat flux, whereas in most western areas latent heat fluxes were reduced. In the EKWs, expansion of irrigated cropland significantly enhanced latent heat fluxes. Changes in latent heat fluxes following expanding irrigated cropland could be partially explained by the fact that irrigation generally enhances evapotranspiration (Wei et al., 2012). However, other indirect impacts associated with changes in the atmospheric circulation may also be responsible for the variations in land surface heat fluxes. For example, reduced latent heat fluxes in the northwestern parts of the wetland areas could possibly be explained by the reduced precipitation and cooling effects of irrigation (Nagler et al., 2007).

Sensible heat flux is mainly determined by temperature differences between land surface and the atmosphere (Yap and Oke, 1974). Heat island effects following urbanization increase local land surface temperature and stimulate heat emissions from land to the atmosphere (Rizwan et al., 2008). Spatial distribution of the differences in sensible heat flux suggested that urbanization greatly enhanced heat flow between land and the atmosphere (Fig. 8A). Results of this study are consistent with previous studies that reported increased sensible heat fluxes and decreased latent heat fluxes following conversions of natural vegetation to built-up surfaces (Kueppers et al., 2008).

Although increases in irrigated croplands mainly reduced air temperature in domain 4 (Fig. 5B), changes in sensible heat fluxes were either positive or negative relative to the real weather simulation. Fig. 8B indicated that in the western and eastern regions of domain 4, sensible heat fluxes were mainly enhanced, whereas in the central regions, sensible heat fluxes were mainly reduced. In the KMDA where land cover was consistent between the two simulations (real weather and irrigated cropland simulations), sensible heat fluxes were also reduced. Thus, results suggested that irrigation may affect energy fluxes in surrounding regions (Stohlgren et al., 1998).

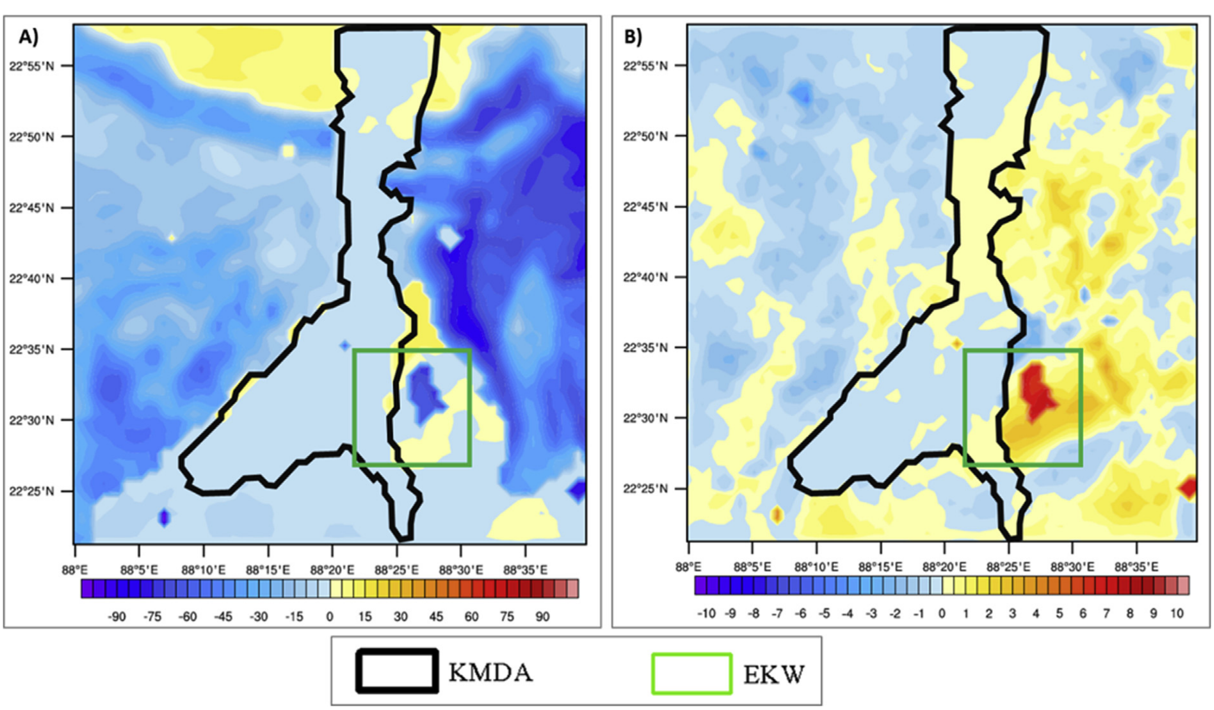

Fig. 7. Changes of mean daily latent heat fluxes (W m^{-2}) following LULC change in domain 4 from November 2011 to January 2012. A) Scenario 1 minus real weather simulation, B) Scenario 2 minus real weather simulation.

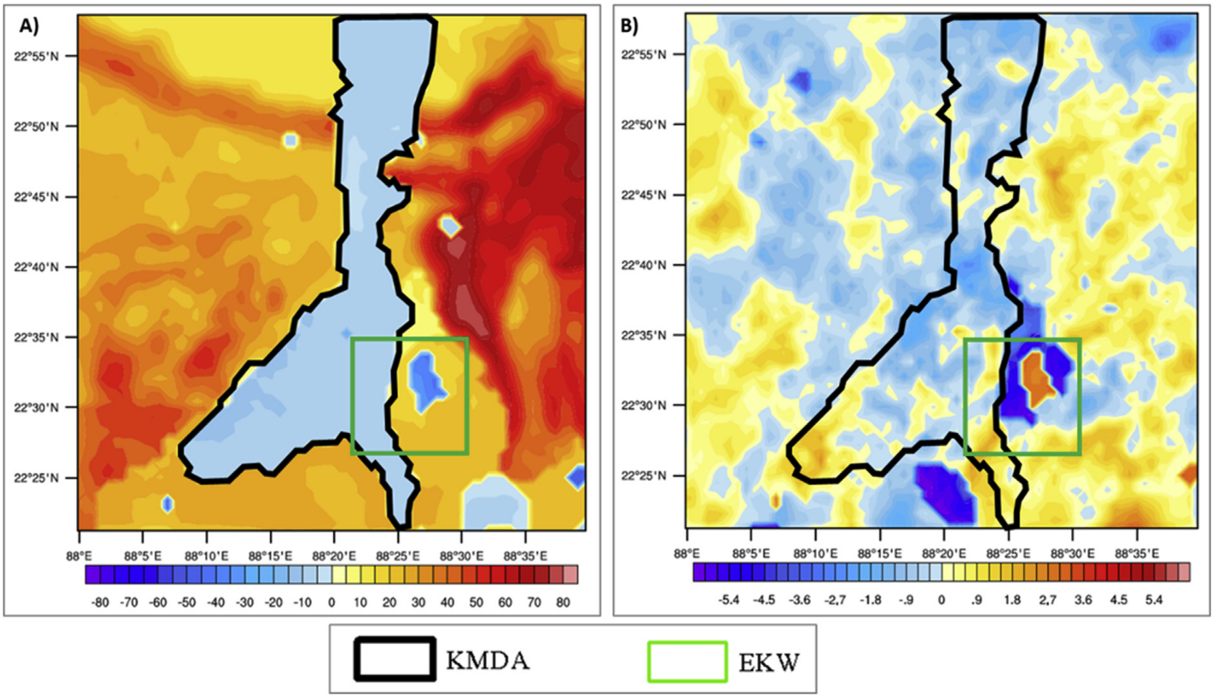

Fig. 8. Changes of mean daily sensible heat fluxes (W m^{-2}) following LULC change in domain 4 from November 2011 to January 2012. A) Scenario 1 minus real weather simulation, B) Scenario 2 minus real weather simulation.

Albedo refers to the fraction of solar energy reflected from the land surface back to the atmosphere. Royer et al. (1988) found a decrease in surface albedo when vegetation was converted to urban areas. The relatively lower albedo in urban areas than croplands may be caused by the multi-reflection effect among buildings (Wang et al., 2007). Besides that, more aerosol emissions in urban area absorb more solar shortwave radiation and lead to a lower albedo of urban (Wang et al., 2007). In this study, decreased albedo was observed around the KMDA when croplands and wetlands were converted to built-up areas (Fig. 9A), which may be a major reason for changes in temperature in domain 4 (Betts, 2001; Myhre and Myhre, 2003).

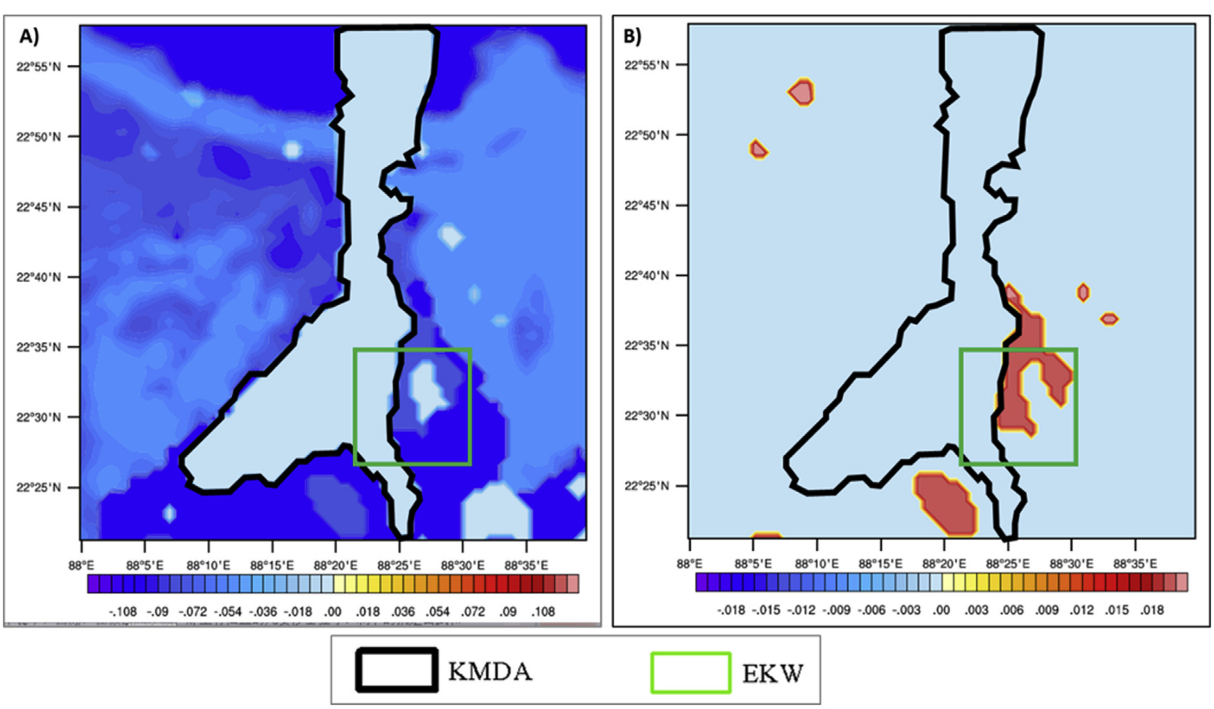

Fig. 9. Changes of albedo following LULC change in domain 4 from November 2011 to January 2012. A) Scenario 1 minus real weather simulation, B) Scenario 2 minus real weather simulation.

Although the replacement of dryland croplands and wetlands by irrigated croplands led to an increase of precipitation and soil moisture, which is usually followed by a reduction of shortwave reflection (Graser and Van Bavel, 1982; Wang et al., 2005), our study found an increased albedo in the irrigated cropland scenario relative to the real weather simulation (Fig. 9B). The result suggested that besides soil moisture, other factors, such as plant types, may also play important roles in determining the albedo in the KMDA.

4.4. Temporal variability of selected variables in response to LULC change

This study also examined the temporal patterns of major meteorological variables in domain 4 from the three simulations (Fig. 10). Results showed that the three simulations generated similar temperature time series during the study period (Fig. 10A). In the real weather simulation and scenario 2, temperatures had decreasing trends with significant variability occurred in January of 2012. Temperature in scenario 1 was higher than the other two simulations, which indicated that urban sprawl could dramatically increase averaged temperature. Due to the changing albedo and hydrological cycles, urban area tended to have higher temperature than other land covers (Ren et al., 2008). Temporal variation of temperature in scenario 1 was similar to that of the other two simulations, and thus suggested that atmospheric circulation played the primary role in determining temporal variability of temperature.

The three simulations agreed well in that no precipitation occurred in November and December of 2011, which is similar to the observational data (Fig. 10B). The simulations were also consistent in the occurrence of rainfall events in January of 2012. However, the magnitudes of rainfall were divergent among the three simulations. For the two rainfall events occurred around December 20th and in the beginning of January, real weather simulation and scenario 2 had similar estimates (Fig. 10B). However, precipitations from scenario 1 during these two events were significantly lower than the other two simulations. Largest discrepancies among the three rainfall simulations occurred around January 7th. For this event, the two land use change scenarios simulated heavier rainfalls than the real simulation.

Changing LULC could largely affect energy exchanges between land and the atmosphere (Douglas et al., 2006). For latent heat flux, both the real weather simulation and scenario 2 showed similar temporal patterns and declining trends during the study period (Fig. 10C). The temporal trends of these two scenarios were similar to that of temperature, indicating that lower temperature may reduce evapotranspiration and associated energy fluxes in January of 2012 (Lamptey et al., 2005). The two scenarios had very close estimates of heat flux magnitudes, especially in the last two months of 2011. In January of 2012, latent energy flux was a bit higher in scenario 1 than that in the real weather simulation. However, increased urban areas in scenario 1 significantly reduced latent heat fluxes relative to the other two simulations. In addition to the magnitude, temporal variability of this index in urbanization scenario was also much lower than the other simulations, suggesting significant impacts of urbanization on heat fluxes between land and the atmosphere (Kueppers and Snyder, 2012).

In contrast to the patterns of latent heat flux, sensible heat fluxes demonstrated increasing trends during the study period (Fig. 10D). Again, real weather simulation and scenario 2 had similar temporal patterns, but scenario 1 had much higher estimates of sensible heat fluxes relative to the other two simulations. Increases in sensible heat fluxes in the urbanization scenario suggested that urbanized land surfaces were important heat sources (Kitada et al., 1998).

4.5. Future work

Note that there are limitations in the WRF simulation because USGS land Use/Land Cover system was used as the default land cover input. As shown in Fig. 1B, the USGS classification does not distinguish EKWs from surrounding croplands, which may increase uncertainties in WRF simulations and inaccurately estimate LULC change impacts on climate. To obtain more precise prediction of microclimate, satellite data with higher spatial resolution are needed to improve the accuracy of land cover input to the model. The EKWs were successfully classified in Li et al. (2016) with overall accuracies ranging from 81.3% to 89.9%. Therefore, future investigation will use improve land use data to better quantify the influence of wetland conversion on microclimate in the study area.

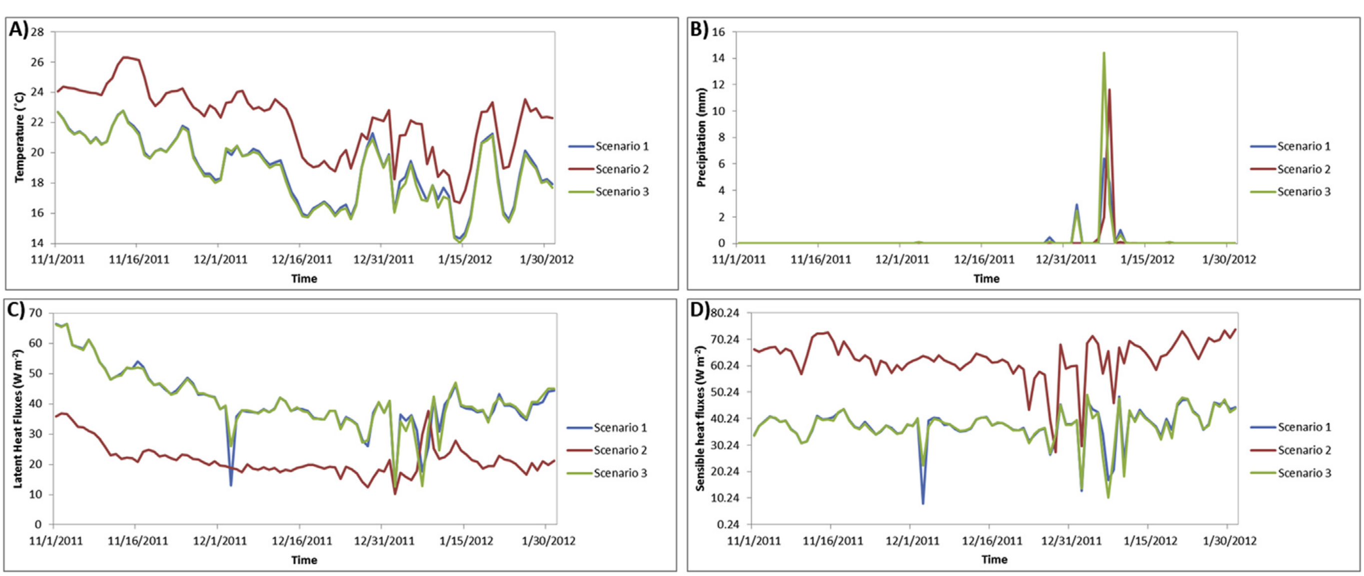

Fig. 10. Comparison of temporal variability in climate variable in domain 4 among three simulations from November 2011 to January 2012. A) temperature (°C), B) precipitation (mm), C) latent heat flux (W m^{-2}), and D) sensible heat flux (W m^{-2}).

5. Conclusions

In this study, WRF Model validation suggested that the model effectively simulated microclimate variability in KMDA. LULC change would substantially influence multiple climate variables. Conversions of wetland and cropland to built-up areas would greatly increase regional temperature and stimulate sensible heat fluxes but reduce latent heat fluxes and albedo. On the contrary, expansion of irrigated croplands could decrease temperature and sensible heat fluxes but increase latent heat fluxes and albedo. The impacts of LULC change on precipitation were complex and a shifting of maximum rainfall rates was observed in the urbanization scenario due to the downwind effect. This study demonstrated the potential effects of urban and agricultural areas increase on climate and would provide valuable supports in assessing the role of LULC change on local hydrology and climate.

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